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THYRISTOR INVERTER FOR ROLLING STOCK

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I. INTRODUCTION

In DC electrified rolling stock, DC series motors have long been used as drive sources since they have ideal characteristics for transport equipment. However, because of the high DC voltages, there is extreme wear in parts with contacts and maintenance and inspection take a long time.

Recently, because of the conversion of many electrical devices to the maintenance free (MF) type, the moving parts of main circuits as well as auxiliary power source equipment for low voltage AC and DC loads are being changed from motor-generator sets containing rotation devices to static type thyristor inverters.

Thyristor inverters are employed as constant voltage/constant frequency (CVCF) types to serve as uninterrupted power sources for general industrial applications where high reliability is required, and as variable voltage/variable frequency types for operation of variable speed motors, etc. Technical and economical problems have been solved through the improvements in the voltage withstand of high speed thyristor elements for relatively large capacities, mass production of the elements and the establishment of high voltage techniques.

Fuji Electric has already completed standardization of inverters for rolling stock. The high voltage inverters manufactured for the Sapporo Traffic Bureau are maintenance free, completely static, vibration proof and enclosed to make them waterproof, dust-proof and fire-proof. The features and characteristics of the Fuji Electric inverter for rolling stock will be outlined here using the 9 kVA unit as an example.

II. INVERTER SPECIFICATIONS

Capacity: Single phase 9 kVA
System: Bridge connection system
Thyristors: GTL 21–12 100 A 1,200 V
Turn off time–less than 50 μs
Arrangement: 2S1P4A
Diode: SIHO1–12 40 A 1,200 V
Arrangement: 2S1P4A
Rated output: Sine wave AC 100 A ±10% 2 kVA
Square wave AC 100 V 4 kVA
DC 100 V 3 kW
Rated frequency: 50 Hz
Frequency accuracy: Less than ±1.5%
Waveform distortion: Less than 10% (AC 100 V)
Rated input voltage: DC 750 V $^{+75}_{-250}$ V
Ratings: 100%-continuous 150%-1 minute
Cooling system: Convection air-cooled
Weight: Approx. 800 kg

III. INVERTER CONSTRUCTION

Inverters for rolling stock have high standard source voltages of 600 V, 750 V and 1,500 V. The construction differs in the following points from that of general industrial inverters.

1) Series connection of the main thyristors and diodes

Since the upper limit of reverse voltage of economical high speed thyristors is 1,300 V at present, the reverse voltage can not be guaranteed unless the number of series connections is 2 or 4 depending on the supply voltage because of the surge voltages in rolling stock and the discharge voltage of lightning arresters. The same can also be said in the case of the diodes even though the reverse voltage is 4,000 V. The problem of these series connections has been completely solved.

2) Interference currents and radio waves

Rolling stock contains communication systems among its electrical equipment and the electrical wiring for rolling stock runs in parallel with various communication systems such as telephone lines. However, since the inverter input current is in the form of a square wave, the percentage of harmonics included is high and considerable interference current and radio waves arise, as well as mutual interference with the ripple frequency of the source voltage. These are minimized by capacitors, etc. and there is no influence to the exterior.

3) Instant stoppage of the power source

Since electrical rolling stock is supplied with power

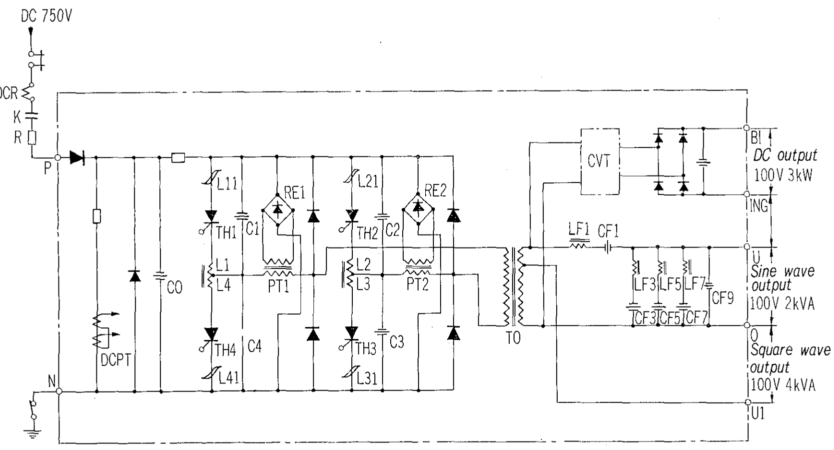


Fig. 1 **Connection diagram of thyristor inverter**

from pantographs, the power source is stopped instantaneously when the pantograph is separated from the overhead wires or a dead section of the overhead wires is passed. In such cases, the instantaneously stopped and restarted stably.

The following is a description of the construction of each part, including the general characteristics.

1. Main Circuit

An outline of the system is given in *Fig. 1.* The thyristors are used Fuji Electric high reverse voltage, high speed thyristors. The circuit system is in the form of a bridge connection consisting of a fundamental side with TH1 and TH4 and a phase shifted side with TH3 and TH2 which fire only after a delay of $\alpha°$ after the fundamental side thyristors. By changing the value of the $\alpha°$, constant voltage of the output is controlled. The commutating circuit required to turn-off the thyristors consists of commutating reactors L1 to L4 and commutating capacitors C1 to C4. Even under the most adverse conditions such as overloads and source voltage drops, sufficient turn off time is assured, the energy of the commutating circuit is held to a minimum and L1 to L4 and C1 to C4 are chosen so that maximum inverter efficiency is achieved.

The thyristors are connected in series with reactors L11 to L41 which have excellent frequency characteristics. Switching loss when the thyristors are turned on or off is minimized.

Highly efficient feedback of the commutating reactor energy to the DC power source is highly important for stable operation, compactness and light weight and efficient application. With the potential transformer feedback system used in this equipment, the commutating reactor energy is changed by the action of the potential transformer from the primary to the secondary sides of feedback transformers PT1 and PT2 as shown in *Fig. 1.* It is then rectified by rectifiers RE1 and RE2 and fed back to the DC power source. This system has the following features when compared with the previous feedback system employing taps in the windings of the potential transformers :

1) Feedback is effective even when the output voltage is zero and the current capacities of the main circuit components such as the thyristors can be much lower.

2) The feedback transformers can be very compact since they need operate only during the damping period of the energy stored in the commutating reactors.

3) Efficiency is high and voltage variations are low

The CO in *Fig. 1* is a capacitor used to stabilize the DC power source, and source voltage variations in respect to load variations, feedback currents, etc. are kept down to a few percent under normal conditions.

Protection against inverter overloads, load short circuits and even commutation loss has been carefully considered and this protection is provided by current limiting using series resistor R on the DC side, as well as the overcurrent relay and high speed breaker K. The output side is insulated from the DC voltage side by transformer TO and the output is divided into sine wave output, square wave output and DC output. A filter is required in the sine wave output circuit in order to separate the sine waves from the square waves. As a results of investigations into filter characteristics, values etc. in order to obtain a waveform distortion within the requirements, the filter circuit shows in *Fig. 1* was chosen. Satisfactory results were obtained as will be shown in the test results given later. The LF1 and CF1 shown in the same diagram form an LC reacter for resonance of the fundamental wave, and LF3 and CF3, LF5 and CF5, and LF7 and CF7 are LC reactors for resonance of the third, fifth and seventh harmonics respectively. CF9 is highly effective against the 9th or higher harmonics.

The DC output is obtained by stabilizing directly the square wave voltage via a ferro-resonance type constant voltage transformer and then rectifying this into stable direct current. Since this is also to be used to charge the storage batteries, it must have constant voltage characteristics, voltage drooping characteristics during overloads and the ripple must be low. These requirements are all satisifed in this equipment through the use of a constant voltage transformer. The transient characteristics in respect to rapid increase in the source voltage, rapid load changes, etc. are also very stable. Generally, when the rectifier load is obtained from an AC power source with a high reactance, the lap angle of the rectifier during commutation is large and there is considerable distortion of the voltage waveform of the AC power source. However, since Fuji Electric employs a system by which the direct current is obtained by rectification of a square wave, there is no waveform distortion of the sine wave output.

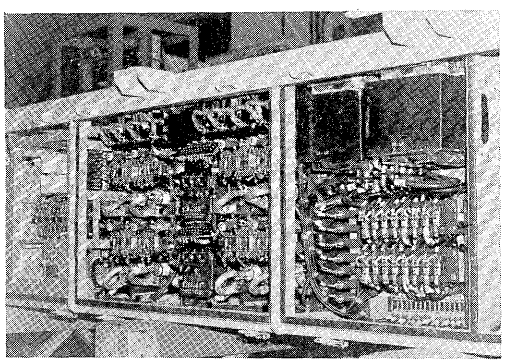
2. Construction

An outer view of the equipment is shown in *Fig. 2*. Cooling is by means of a convection air cooling system. Devices placed on rolling stock must be compact, lightweight and easy to inspect. There are therefore many structural limitations. The following points were considered in the construction of this equipment.

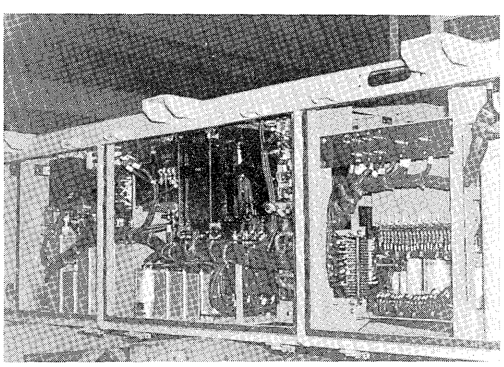
1) The transformers and reactors were provided with H or E class insulation and the equipment was designed to be compact and light weight.

2) Heavy parts were arranged so that no undue mechanical force is exerted on the frame by lowering such parts from above.

3) The thyristors and control parts are arranged so that it is very easy to check and maintain them from the exterior.



(a) Front view



(b) Back view

Fig. 2 Outer view of thyristor invertor

4) The control circuit components are all assembled on printed boards accomodated in a single box which can be pulled out.

5) Shielding is provided for parts with high generative losses and effects on other parts due to heat are minimized.

6) The choke coil and other parts are provided with epoxy resin moldings which keep the noise extremely low.

7) All of the boxes are completely enclosed so that they are water- and dust-proof.

3. Control Circuitry

1) Outline

Constant voltage/constant frequency inverters have the constant voltage controlled by means of pulse width conducting control and the fundamental frequency is determined by means of an astable multivibrator with a small range of variation.

When there is any abnormality in the power supply for the rolling stock equipment, the inverter is stopped by pulse control without misoperation and after power supply recovery, stable restarting takes misoperation and after power supply recovery, stable restarting takes place. If the power supply is suddenly increased or decreased, output voltage variations are kept small by the use of a phase shifting regulator with good transient response. This is especially effective when the inverter output serves as the power supply for communication equipment.

2) Circuit components

A block diagram of the circuit is shown in *Fig. 3*. An astable multivibrator is used for the fundamental oscillator circuit. However, this circuit oscillates at the frequency 2f which is twice the inverter output

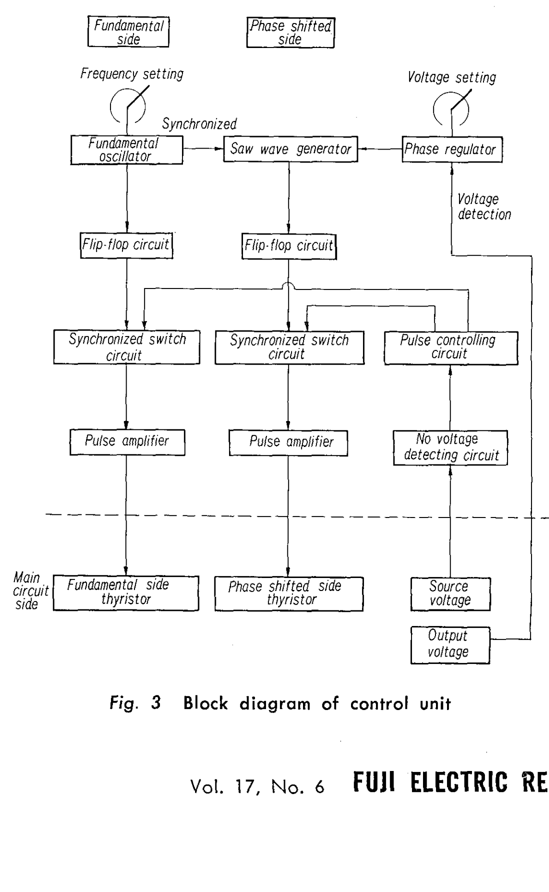


Fig. 3 Block diagram of control unit

frequency (f). This 2f square wave pulse is halved by means of flip-flop (FF) and becomes the frequency f. These is a synchronized switch between the flip-flop and pulse amplifier (PA) and this will be described later. The flip-flop output enters the pulse amplifier and is transmitted in the sequence : pulse amplifier→ pulse transformer→fundamental side thyristors. It then operates the arm on the fundamental side of the inverter. On the phase shifted side, the difference between the detected value and the set value of the sine wave output voltage first enters the phase shifting regulator. It is then amplified by the integrated circuit and becomes the controlling voltage. The phase relation between the fundamental side and the phase shifted side is determined and the phase shifted pulse is oscillated. All operations after the flipflop are the same as on the fundamental side.

Frequency accuracy according to actual measurements and tests was as follows :

Source voltage characteristics :

$\leqq \pm 0.1$ Hz/50 Hz at 10% voltage regulation of control circuit power supply.

Temperature characteristics :

$\leqq \pm 0.2$ Hz/50 Hz (−10°C to +50°C)

$\leqq \pm 0.5$ Hz/50 Hz (−30°C to +70°C)

3) Use of the synchronized switch

Power supplied to the rolling stock is obtained from the overhead wires by means of an accumulator. However, variations are considerable when the overhead wires voltage suddenly increases (+20%) or decreases (−40%), or stoppage occurs because of separation of the wires or passing a dead section. The synchronized switch is provided so that the inverter will operate stably when there are abnormalities or sudden changes in the power supply.

(1) During stoppage

The inverter is stopped when there is no main circuit source voltage. The inverter is stopped in such cases by no-voltage detection.

If a wire separation is detected when the load current is flowing in TH1→load→TH3 (① direction) as in *Fig. 4*, pulse transmission is stopped when TH1 and TH2 are conducting, and the inverter is stopped. When the power supply recovers, the wire separation is removed and restarting occurs, the initial load current flows in the ① direction and output transformer saturation is eliminated. When the load current is flowing in TH2→load→TH4 (② direction) and a wire separation is detected, pulse transmission is stopped when TH3 and TH4 are conducting, and the inverter is stopped. When restarting occurs, the initial load current flows in the ② direction.

The period after the time when the separation is detected until the inverter is stopped, is within one cycle, but when the voltage of the ballast capacitor CO on the main circuit input side is below the commutation ability limit voltage, commutation occurs. Therefore. it is necessary to insure that there is a time tolerance of more than 1 cycle by making the CO capacity large.

(2) During starting

When the source voltage is larger than the wire separation detection voltage, power source recovery is detected and the inverter is restarted. The static switch is placed in the ' ON ' state by synchronization with the flip-flop output, the inverter is restarted and a soft start takes place. However, the thyristor firing pulse is about 180° different from the initial pulse and inverter starting loss can be eliminated.

As was mentioned above, the static switch is operated by synchronization with the established flip-flop output pulse and the inverter is started or stopped. Therefore, this pulse control circuit is known as a synchronized switch.

IV. TEST RESULTS

This high voltage inverter has already proven its capabilities in the actual train. However, data from the most severe tests are described below.

1) Input voltage regulation test

The guaranteed values for the inverter in respect to power supply changes inherent in rolling stock are 500 to 825 V for a rated input voltage of 750 V. The oscillogram for the input voltage regulation test is shown in *Fig. 5*. As is evident from this figure, operation is stable and the response is good for the waveforms of other parts and severe tests. In particular, one part satisfies the requirements for transient response of DC output voltages used also in communication equipment power supplies.

2) Momentary supply interruption test

In rolling stock, there are many cases of power interruptions such as separation from the overhead

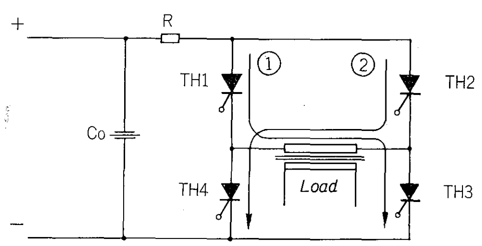


Fig. 4 Schematic diagram of thyristor inverter

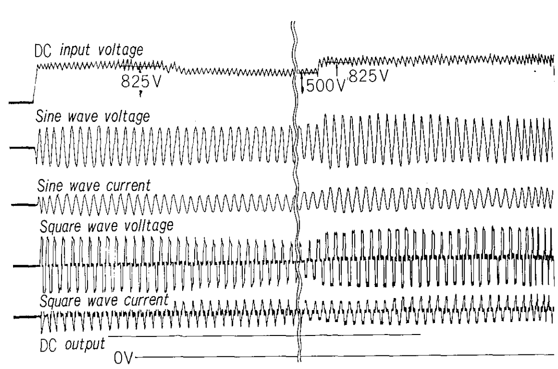


Fig. 5 Oscillogram of each waveform at supply voltage regulation

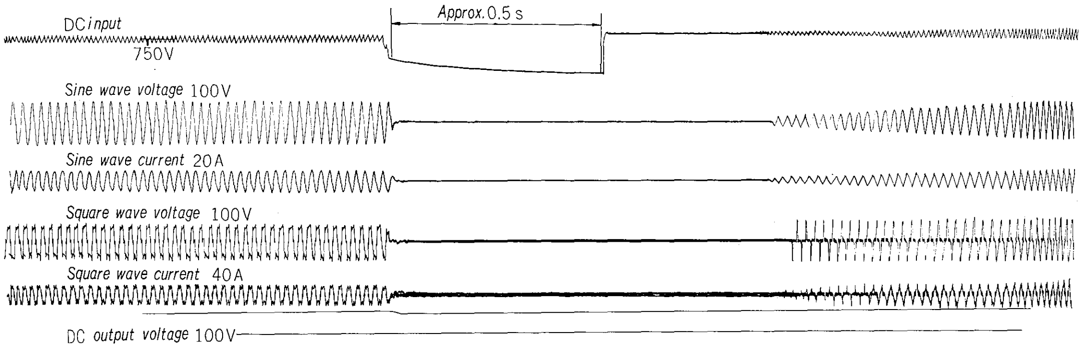


Fig. 6 Oscillogram of each waveform at momentary supply voltage off

wires, passing through dead sections, etc., but when the power supply is interrupted, the inverter stops and is restarted only after power supply recovery. *Fig. 6* shows an oscillogram from this test. During stopping, the output voltage is suddenly minimized, the pulse is stopped and a soft start is made at the time of restarting.

3) Others

Good results were obtained in all other tests such as temperature rise tests, vibration tests and tests of various characteristics in respect to input voltage and load changes. Various tests were conducted under the climatic conditions found in Sapporo, particularly in relation to low temperature characteristics. Good results were obtained over an ambient temperature range of −30°C to +40°C.

For the sine wave output, waveform distortion was considered and care was taken so that there is no flicker when fluorecent lights are the load. Under rated load conditions, less than 4% is obtained.

V. CONCLUSION

The above has been a brief report on a high voltage thyristor inverter for rolling stock. As one step in making rolling stock maintenance free, equipment using semiconductors will no doubt be employed more and more in the future. Fuji Electric is engaged in the rationalization of this type of equipment.

Finally, the authors wish to thank all those persons in the Sapporo Traffic Bureau and Kawasaki Heavy Industries who gave their cooperation and guidance concerning this equipment from the trial to the manufacturing stages.